Recent progress and future plans for ultra-high granularity CMOS ECAL

- Nigel Watson (Birmingham)
Cross-detector concept R&D

Mainly organised within the: CALICE Collaboration

- Particle flow approach → high granularity calorimeter
- How granular? Move from analogue energy deposit to shower particle counting
- (Ultra) high granularity calorimeter
  - Reduce contribution to resolution from Landau fluctuations
  - Very good two-shower separation and position resolution
DECAL Concept for SiW ECAL

- Swap ~0.5x0.5 cm² Si pads with small pixels
  - at most one particle/pixel, for 1-bit ADC/pixel – binary approach
- Avoid saturation/non-linearity…
  - EM shower core density at 500GeV ~100/mm²
  - Pixels size <100x100μm²
  - ~10^{12} pixels for ECAL barrel

- Simpler construction (no bump bonding)
- DECAL prototypes to date 180 nm process → 65nm
- Performance gains? Tracking highly boosted decays, e.g. \( \tau, \pi^0 \rightarrow \gamma\gamma \) …
- Effectively a ‘tracking calorimeter’
DECAL prototype reality: EPICAL-2

- Layer cable
- Chip cable
- ALPIDE
- SMD flex
- mount
- Spacer 0.5mm
- Tungsten
- absorber 3mm

24 layers, each
- 3 mm W / 2 ALPIDE CMOS
- 3 x 3 cm² active
- 1M (29.24 x 26.88 μm²) pixels
- ultra-thin flex cables (LTU Kharkiv)
- compact design: expect $R_M \approx 11$ mm
**Event Display**

- one-electron event
  - 5 GeV
  - raw data

→ detailed evolution of shower

- color coding: layers
Preliminaries: aligning layers

- Selected sample of 5k cosmic muons in lab
- After alignment, residuals < 5\(\mu\text{m}\)

[\textit{JINST} 18 (2023) 01, P01038]
Preliminaries: aligning layers

• Selected sample of 5k cosmic muons in lab
• After alignment, residuals < 5µm

[JINST 18 (2023) 01, P01038]
Event selections ensure:
- Lateral containment
- Single particle showers

Basic clustering and pixel hits similar

Calibration of sensors (supply voltage, temperature, FE discriminators) using cosmics:
- Use cosmic muons
- Separately for hits/clusters
- Good uniformity (single global threshold/512k pixel sensor)

[JINST 18 (2023) 01, P01038]
EPICAL-2 simulation utilizing Allpix\textsuperscript{2}\ I

A Monte Carlo simulation tool for silicon pixel detectors
From incoming particle(s) to readout

**simulation chain:**

- geometry builder
- electric field initialization
- energy deposition

- electric field obtained from **TCAD** simulation by Jan Hasenbichler
- total reverse bias voltage of $V_{RB} = 1.4\ \text{V}$

Data modelled well

- particle transport and deposition of charges in active materials

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[Diagram of diodes and active material]

https://indico.cern.ch/event/813597/contributions/3727778/attachments/1989124/3315600/Trento_Workshop_Hasenbichler.pdf
Simulating tails

- Simulation models even rare large clusters found in data

EPICAL-2 Simulation Layer 4 (LHS), 5.0 GeV

EPICAL-2 Data Layer 5 (RHS), 5.0 GeV
**Shower profiles**

- Hits and clusters similar
- Described well by AllPix2 simulation

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[JINST 18 (2023) 01, P01038]
Energy response fits: details

**Table 2:** Mean $\mu$ and standard deviation $\sigma$ of $N_{\text{hits}}$ and $N_{\text{clus}}$ distributions in data for electron energies 1.0–5.8 GeV.

<table>
<thead>
<tr>
<th>data</th>
<th>hits</th>
<th>clusters</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_0$ (GeV)</td>
<td>$\mu$</td>
<td>$\sigma$</td>
</tr>
<tr>
<td>1.0</td>
<td>291.63 ± 0.13</td>
<td>71.65 ± 0.09</td>
</tr>
<tr>
<td>2.0</td>
<td>574.17 ± 0.22</td>
<td>100.05 ± 0.16</td>
</tr>
<tr>
<td>3.0</td>
<td>862.39 ± 0.26</td>
<td>123.20 ± 0.19</td>
</tr>
<tr>
<td>4.0</td>
<td>1141.96 ± 0.25</td>
<td>140.80 ± 0.18</td>
</tr>
<tr>
<td>5.0</td>
<td>1417.88 ± 0.20</td>
<td>157.14 ± 0.14</td>
</tr>
<tr>
<td>5.8</td>
<td>1613.99 ± 0.29</td>
<td>170.08 ± 0.20</td>
</tr>
</tbody>
</table>

**Table 3:** Mean $\mu$ and the standard deviation $\sigma$ of the $N_{\text{hits}}$ and $N_{\text{clus}}$ distributions in simulation for electron energies 1.0–5.8 GeV.

<table>
<thead>
<tr>
<th>simulation</th>
<th>hits</th>
<th>clusters</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_0$ (GeV)</td>
<td>$\mu$</td>
<td>$\sigma$</td>
</tr>
<tr>
<td>1.0</td>
<td>286.20 ± 0.32</td>
<td>75.48 ± 0.22</td>
</tr>
<tr>
<td>2.0</td>
<td>568.8 ± 0.4</td>
<td>96.71 ± 0.30</td>
</tr>
<tr>
<td>3.0</td>
<td>853.1 ± 0.5</td>
<td>116.11 ± 0.35</td>
</tr>
<tr>
<td>4.0</td>
<td>1136.7 ± 0.6</td>
<td>131.4 ± 0.4</td>
</tr>
<tr>
<td>5.0</td>
<td>1418.1 ± 0.6</td>
<td>145.6 ± 0.5</td>
</tr>
<tr>
<td>5.8</td>
<td>1643.5 ± 0.7</td>
<td>155.7 ± 0.5</td>
</tr>
</tbody>
</table>
Calorimetric performance

Data Sim.

- Hits
- Clusters
- EPICAL-1 hits
- Linear fit

<table>
<thead>
<tr>
<th></th>
<th>$a$ (%)</th>
<th>$b$ (%)</th>
<th>$c$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>hits data</td>
<td>24.30 ± 0.03</td>
<td>2.41 ± 0.08</td>
<td>-</td>
</tr>
<tr>
<td>sim ($E_{\text{spread}} = 0$)</td>
<td>21.27 ± 0.06</td>
<td>2.30 ± 0.16</td>
<td>-</td>
</tr>
<tr>
<td>sim ($E_{\text{spread}} = 158$ MeV)</td>
<td>21.58 ± 0.25</td>
<td>1.8 ± 0.5</td>
<td>15.1 ± 0.4</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>$a$ (%)</th>
<th>$b$ (%)</th>
<th>$c$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>clusters data</td>
<td>18.54 ± 0.02</td>
<td>2.17 ± 0.05</td>
<td>-</td>
</tr>
<tr>
<td>sim ($E_{\text{spread}} = 0$)</td>
<td>14.10 ± 0.04</td>
<td>2.52 ± 0.07</td>
<td>-</td>
</tr>
<tr>
<td>sim ($E_{\text{spread}} = 158$ MeV)</td>
<td>14.57 ± 0.21</td>
<td>1.96 ± 0.26</td>
<td>14.93 ± 0.23</td>
</tr>
</tbody>
</table>

\[
\frac{\sigma_E}{E} = \frac{a}{\sqrt{E/\text{GeV}}} \oplus \frac{b}{E/\text{GeV}} \oplus \frac{c}{E/\text{GeV}}
\]

- Good standard performance
- Better resolution from clusters
- Uncertainties in beam energy spread
Benefit of ultra-high granularity separation power

- same energy
- electrons separated by ~ 7.2 mm
Benefit of ultra-high granularity separation power

- large energy difference
- electrons close together
  → challenging case

250 GeV electron
30 GeV electron

EPICAL-2 preliminary simulation
Allpix² simulation
default settings

71887 hits

EPICAL-2 preliminary simulation
Allpix² simulation
default settings

electron energy (%)

hits/µs

clusters/µs
Benefit of ultra-high granularity separation power

- large energy difference
- electrons close together

→ challenging case

EPICAL-2 preliminary simulation
Allpix² simulation
default settings

250 GeV electron
30 GeV electron

EPICAL-2 preliminary simulation
Allpix² simulation
default settings
Future Opportunities for DECAL

• **Si-W calorimetry can give excellent PFA performance**
  ▶ Potential for reconfigurable technology: outer tracker/preshower/ECAL
    ▪ I.Kopsalis et al, NIM A1038 (2022) 166955
    ▪ P.P.Allport et al, Sensors 2022, 22(18) 6848

• Affordable Si-W calorimeters, sensors ~ CHF/cm² (active areas > 10⁷cm²)
  ▶ Potentially achievable with CMOS MAPS

• Power needs study, CMOS estimates range ~50-100mW/cm² (no pulsing)

• Prototype demonstrating concept of digital ECAL, in same CMOS line as CERN et al, can deliver radiation hardness to > 10¹⁵neq/cm²

• **Digital EM calorimetry, high potential esp. for future e⁺e⁻**
  ▶ Ultra-high granularity can benefit physics as well as cost (boosted decays)
  ▶ Calorimetric performance demonstrated
  ▶ Existing data with EPICAL-2 up to 80 GeV / SPS (analysis in progress)
  ▶ Enhance with optimised sensor development
  ▶ ECFA DRD proposal and interested in collaborate widely 😊

[Thanks to Roman Poeschl, Tim Rogoschinki, Thomas Peitzmann and others!]
backup
DECAL (4mm×4mm Array) Prototype Chip

Concept in FCC-hh context of a common silicon development for:
- Outer tracking
- Pre-shower
- EM calorimeter

Reconfigurable sensor as:
- 5mm×50μm strips
- 5mm×5mm pad

Prototype as proof of concept (180nm CMOS*)

Strip mode
64 strip array
64 x 64 pixels

Pad mode

<table>
<thead>
<tr>
<th>Specification</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pixel Pitch</td>
<td>um</td>
<td>55</td>
</tr>
<tr>
<td>Resolution</td>
<td>pix</td>
<td>64 x 64</td>
</tr>
<tr>
<td>Frame Rate</td>
<td>MHz</td>
<td>40</td>
</tr>
<tr>
<td>Input Referred Noise</td>
<td>e- rms</td>
<td>80</td>
</tr>
<tr>
<td>Max hits/col (pad mode)</td>
<td>hits</td>
<td>15</td>
</tr>
<tr>
<td>Max hits/col (strip mode)</td>
<td>hits</td>
<td>3</td>
</tr>
</tbody>
</table>

Information on up to 3 hits per column gives data rate 5.12Gb/s

Information on up to 15 hits per column giving 240 hits per pad gives data rate of 2.56Gb/s

*TowerJazz (Small collection node)